International Journal of the Korean Society of Precision Engineering Vol. 3, No. 3, July 2002.

Improvement of Contour Fringes by using Addition of Incremental Images

Young-June Kang[1], Weon-Jae Ryu[2] and Sang-Kyu Park[3]

[1] Faculty of Mechanical Engineering, Chonbuk National University, Mechatronics Research Center, Jeonju, Korea
[2] Graduate school, Department of Mechanical Design, Chonbuk National University, Jeonju, Korea
[3] Department of Automotive Engineering, Woosuk University, Jeonju, Korea

ABSTRACT

Electronic speckle contouring(ESC) based on electronic speckle pattern interferometry is the optical method for measuring object shape by using fringe-projection techniques. This method has the advantages of being non-contact, non-destructive and a whole-field measurement of the surface under investigation. Fringes in ESC represent the difference in depth along the view direction between the master wavefront and the test component.

The contour maps of three-dimensional diffuse objects can be obtained by small shifts of optical fiber carrying the dual-object-beams and 4-frame phase shifting.

In this study we proposed the contouring method by shifting the collimated illumination beams through optical fiber in order to obtain the contour fringe patterns. And also, we performed the addition of incremental images through the geometrical analysis to obtain the contour fringe interval when we performed the incremental addition of images and experiments based on this method. We obtained both quantitative increment without decorrelation effect and qualitative improvement by reducing the noise of contour fringes.

Keywords: Electronic Speckle Pattern Interferometry, Phase Shifting, Geometric Analysis, Electronic Speckle Contouring, Incremental Addition Image Method

1. Introduction

The Electronic Speckle Pattern Interferometry(ESPI)[1] developed by Butters and Leendertz in 1969 has made rapid progress as a non-contact and non-destructive measuring method. Since the latter of the 1970's this method has been applied to many fields such as the aircraft, nuclear power plant, automobile industry, and construction industry. Electronic Speckle Contouring(ESC) is the object shape measurement method by using Electronic Speckle Pattern Interferometry.[2-5] Traditional 3-D shape measurement machine(CMM) and the optical methods using point or line scanning have the drawbacks such as the time-consuming and the limit of measurement region. But it overcomes them because ESC can measure the full-field of object under a laser illumination.

ESC can obtain the fringes of regular contour interval according to the height and shape of the object and acquire the shape information of 3-D object by the image processing. In the previous papers, the geometric analysis of contour fringe formation process and the characteristics of contour fringe were explained in detail.[6]

In this paper, the 3-D object shape measurement was performed by using the collimated beam and the phase-shifting method[7]. And the incremental addition image method[8-10] was used for an increase in quantity and improvement in quality. The contour height calculation of 3-D object was executed by using the incremental addition images and 3-D shape measurement was accomplished by using the collimated beam for the analysis of interferometer performance. Finally, the limit of displacement cause by decorrelation effect of fringe was able to improve.

2. Analysis theory of the fringe pattern

In ESPI, the fringe intervals are related to the deformation amount of an object and the wavelength of the light source and determined by the phase difference. If it is concerned with an object height, the Electronic Speckle Contouring(ESC) is the method that is able to measure the 3-D shape of an object by analysing the fringe patterns resulted from the phase difference.

In this study, the shifting method of the dual beam is used to measure the shape. In the previous study, the theoretical equation of the fringe intervals was derived and the relationship between the fringe intervals and the object height was established by analyzing the geometric structure in Fig. 1. Also, the theoretical equation of the fringe intervals in the incremental image addition method is derived on the basis of the ones in the previous study.[6]

In Fig. 1, the dual beam arrive at the view point, P via M, a point on the object. Here, $\Delta\theta$ is the shifting angle to measure the shape of an object. In the incremental addition method, the constant shifting angle($\Delta\theta$) is applied repeatedly and the images are added. Therefore, the total shifting angle of the n-th incremental addition image becomes $n\Delta\theta$.

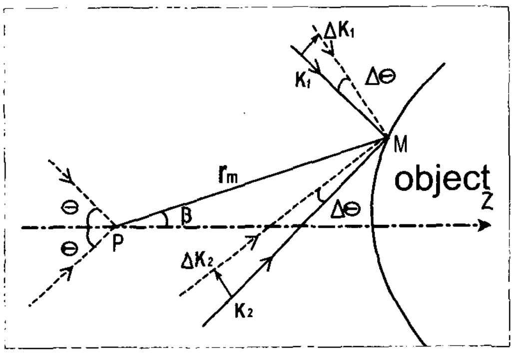


Fig. 1. Geometry of dual-beam-shifted electronic speckle contouring.

An speckle pattern is formed by the dual illumination beam. And the phases(Ψ_{m1}, Ψ_{m2}) before and after the deformations of the obtained speckle patterns are expressed by the following equations[5].

$$\Psi_{m1} = \frac{2\pi}{\lambda} r_m \cdot (K_1 - K_2)$$
$$\Psi_{m2} = \frac{2\pi}{\lambda} r_m \cdot (K_1' - K_2') \tag{1}$$

where,

K_1, K_2 : unit direction vector of two waves before the deformation.

K'_1, K'_2 : unit direction vector of two waves after the deformation.

λ : wavelength of the illumination beam.

r_m : position vector

From the above equations, the phase difference ($\Delta\Psi_m$) between before and after the deformation can be described by Eq. (2).

$$\begin{aligned} \triangle\Psi_m &= \Psi_{m2} - \Psi_{m1} \\ &= \frac{2\pi}{\lambda} r_m \cdot (\triangle K_1 - \triangle K_2) \\ &= \frac{2\pi}{\lambda} |r_m| |\triangle K_1 - \triangle K_2| \cos\beta \end{aligned} \tag{2}$$

where, ΔK_1, ΔK_2 : vector difference between before and after the deformation

When the illumination angle(θ) is shifted n-times as much as $\Delta\theta$, the n-incremental images are added sequentially. Then, the phase difference($\Delta\Psi_{mn}$) of the n-incremental images can be described by Eq. (3) and Eq. (4).

$$\begin{aligned} \triangle\Psi_{mn} &= (\Psi_{m(n+1)} - \Psi_{mn}) + (\Psi_{mn} - \Psi_{m(n-1)}) \\ &\quad + \cdots\cdot + (\Psi_{m2} - \Psi_{m1}) \\ &= (\Psi_{m(n+1)} - \Psi_{m1}) \end{aligned} \tag{3}$$

$$\begin{aligned} \triangle\Psi_{mn} &= \Psi_{m(n+1)} - \Psi_{m1} \\ &= \frac{2\pi}{\lambda} r_m \cdot (\triangle K_1^n - \triangle K_2^n) \\ &= \frac{2\pi}{\lambda} |r_m| |\triangle K_1^n - \triangle K_2^n| \cos\beta \\ &= \frac{2\pi}{\lambda} (2\sin\theta) r_m \cos\beta \, n \triangle\theta \end{aligned} \tag{4}$$

where,

$$\triangle K_1^n = K_1^{(n+1)} - K_1$$
$$\triangle K_2^n = K_2^{(n+1)} - K_2$$
$$|\triangle K_1^n| = |\triangle K_2^n| = n\triangle\theta\,|K_1|$$
$$= n\triangle\theta\,|K_2| = n\triangle\theta$$

If h is $r_m\cos\beta$ and also ΔK_1 and ΔK_2 are axis-symmetric about Z-axis, h becomes height of the object in Z-axis. Finally, the contour depth of the n-th incremental addition images can be expressed by the following equation.

$$d = \frac{\lambda}{2n\sin\theta\triangle\theta} \tag{5}$$

This equation implies that the sensitivity of the n-th incremental addition image becomes small as much as one nth In other words, it means that displacement and shape measurement region can be increased with an increase of the sensitivity. And the contour depth from Eq. (5) is used to measure an object shape as a sensitivity.

3. The phase-shifting method

The phase-shifting method has been widely used to analyze fringe patterns formed on the object, and the phase of one beam is shifted relatively to the phase of the other by the PZT(piezoelectric transducer) element. The fringe patterns have the deformed information of the object. But it is not easy to judge whether the surface is convex or concave. So the phase-shifting method is used.

To find the phase of the object deformation, the phase of speckle patterns of before and after deformation is simply subtracted electronically.

The light intensity ($I_i(x,y)$) formed by speckle patterns, a point on the surface (x,y) to be measured can be expressed in the following equation[7]:

$$I_i(x,y) = I_0\{1+\gamma(x,y)\cos[\phi(x,y)+\alpha_i]\}$$
$$i = 1, 2, 3, 4 \tag{6}$$

Where I_0 is the average intensity, $\gamma(x,y)$ the modulation of the fringe pattern, α_i the average value of the relative phase shift for the ith exposure, and $\phi(x,y)$ is the interference phase of the wavefront on the measured surface(x,y).

The four-frame phase shifting method is used for phase calculation. For each image frame, the intensity is obtained by using a reference mirror linearly moved by a PZT through a π /2 change in phase. In this case, the intensities of the four recorded images can be written as

$$I_1(x,y) = I_0(x,y)\{1+\gamma(x,y)\cos[\phi(x,y)]\} \tag{7-1}$$
$$I_2(x,y) = I_0(x,y)\left\{1+\gamma(x,y)\cos[\phi(x,y)+\frac{\pi}{2}]\right\} \tag{7-2}$$
$$I_3(x,y) = I_0(x,y)\{1+\gamma(x,y)\cos[\phi(x,y)+\pi]\} \tag{7-3}$$
$$I_4(x,y) = I_0(x,y)\left\{1+\gamma(x,y)\cos[\phi(x,y)+\frac{3\pi}{2}]\right\} \tag{7-4}$$

$$I_4(x,y) - I_2(x,y) = 2I_0(x,y)\gamma(x,y)\sin\phi(x,y) \tag{8-1}$$
$$I_1(x,y) - I_3(x,y) = 2I_0(x,y)\gamma(x,y)\cos\phi(x,y) \tag{8-2}$$

The interference phase on the measured surface (x,y) is

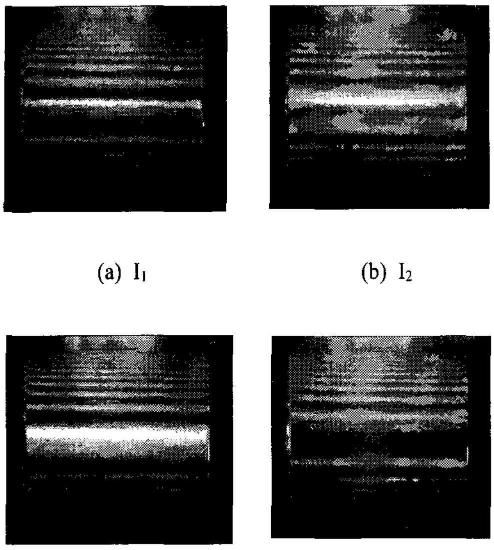
$$\phi(x,y) = \tan^{-1}\left[\frac{I_4(x,y)-I_2(x,y)}{I_1(x,y)-I_3(x,y)}\right] \tag{9}$$

Fig. 2 shows the obtained fringe patterns by using the Eq. (7-1), (7-2), (7-3) and (7-4). And Fig. 3 is the obtained phase map by using the Eq. (9).

Because of the nature of arctangent, the computed phase is wrapped into the range -π and +π . Finally, not only an unwrapped phase distribution but also the amount of displacement formed on the object was obtained by using the phase unwrapping.

4. Incremental addition image

The incremental addition image method used in this study can lead out the final deformation and improve the fringe quality by adding the image of the same deformation shifted reguraly.



(a) I_1 (b) I_2

(c) I_3 (d) I_4

Fig. 2 Phase shifted images

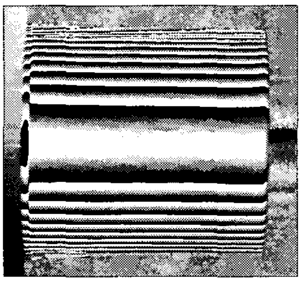


Fig. 3 The phasemap calculated from Fig. 2

In ESC, the greater deformation occurs the more number of fringes show up. As a result, the decorrelation effect comes up. These phenomena make the visuality of the fringe worse and the phase information vanishes.

So the incremental addition image method can not only induce the final displacement but also decrease the decorrelation effect of the fringes. And then it improves the fringe quality by decreasing the noises.

In the incremental addition image method, the collimated beam is used to measure the shape of 3-D object. When diffused beam is used, speckle patterns itself are the informants. Thus, the shift of the beam increases, the decorrelation effect as well as noise increases. It makes the fringe non-homogeneous in the incremental addition image process. Also, it is difficult to lead out the exact information of deformation. Therefore, we used collimated beam as informant. Additionally, we have proved an important thing through experiments. If the same image is used in the incremental addition image, we can get the quantitative improvement of the fringe without the decorrelation effect. But it has no effect on the fringe quality because the noise is not removed. Therefore, the constantly shifted or increased images should be used.

Table 1 shows the relation among the shift steps of the object beam, the sets of four intensity patterns and the phase-deformation fringe patterns. The qualitatively improved image of the nth incremental addition image can be obtained without the decorrelation effect through repeating the shift step and the incremental addition.

Table 1. The relations among the shift steps of the object beam, speckle-phase patterns (sets), and phase-deformation fringe patterns

Object beam	Sets (of four intensity patterns)	Phase-deformation fringe patterns
Undeformed	1	
1.shift step	2	1. corresponds to sets 1 and 2
2.shift step	3	2. corresponds to sets 2 and 3
.	.	
.	.	.
i.shift step	i + 1	ith corresponds to i and I+1
.	.	
.	.	.
N.shift step	N + 1	Nth corresponds to sets N and N+1

5. Experimental set-up

The optical arrangement for the shape measurement of 3-D object is shown in Fig. 4 and it is set on the optical table of 1.5m×3m size for isolating the vibration of surroundings. The light source is Nd:Yag laser(100mW) with the 532nm wavelength and the CCD camera is used to acquire the image. The achromatic lens is used to collimate the laser beam. The single mode optical fiber is used for easy movement of the laser beam.

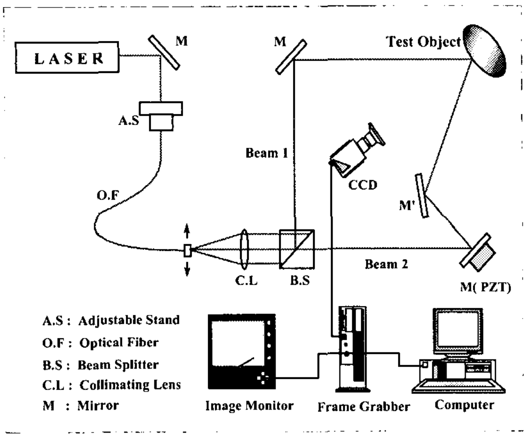


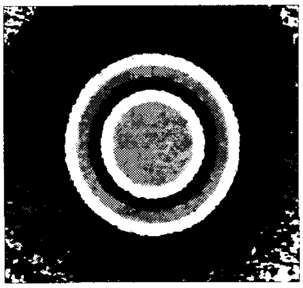
Fig. 4 Schematic diagram of speckle interferometer for dual-beam-shifted electronic speckle contouring

In order to perform 4-frame phase-shifting method, the PZT is adhered to one mirror on the dual object beams' path. The laser beam is delivered directly into a single-mode optical fiber and then the laser beam through the optical fibers loses partially at the entrance and in the fiber. So 65% of the laser beam outputs as traverse-mode(TEMoo). Because the optical fiber serves as the expander in itself, the expanded laser beam is collimated by the collimating lens. The laser beam is divided into two parts by a beam splitter and the dual beams are illuminated on the surface of 3-D object with an incident angle θ =23.5 degree. The optical path length(OPD) of the dual beams is $l_1 = l_2$ =141cm.

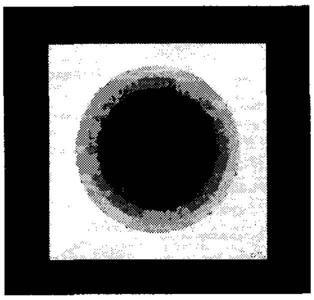
6. Experimental results and discussion

In this study, a collimated beam that is based on ESPI is used for the 3-D shape measurement and the incremental addition image is performed to increase the quantity and improve the quality of the fringe.

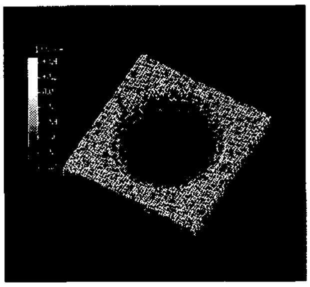
The diffused laser beam in optical fiber is collimated by a lens. This collimated beam is moved between right and left by the micrometer which is constructed at the lower part of optical fiber. This movement is used to measure the shape and to display the height contour of fringe with the shape information. Also the incremental addition method is performed, while the movement is shifted in the regular small quantity precisely for one direction.



(a) Phase map



(b) Demodulated image



(c) 3-D plot

Fig. 5 The experimental results obtained when the illumination angle θ is 23.5°and the angel difference $\triangle\theta$ is 1.182 mrad

Fig. 5 displays the results with the 3-D shape information and the contour of fringe. This contour is the fringe pattern of specimen whose the height is 200㎛ and the width is 1㎜.

When the optical fiber is shifted as much as 130㎛ by micrometer and rotated 1.182 mrad, the distance of contour is d=0.563㎜. Fig. 5(a) displays the phase map obtained by the 4-frame phase shifting method. The phase shifting is performed as much as π /2 by PZT to analyze quantitatively. Fig. 5(b) is unwrapped image and Fig. 5(c) is the result of 3-D plot from unwrapped image.

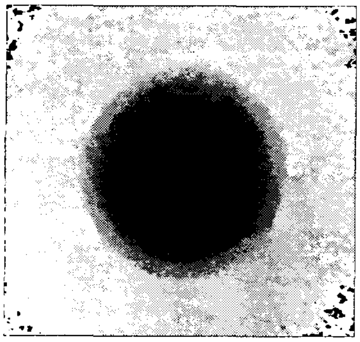
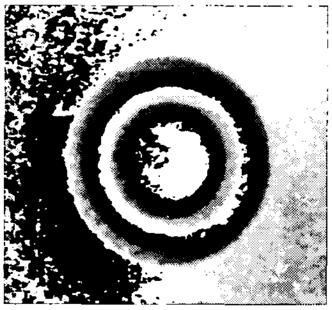


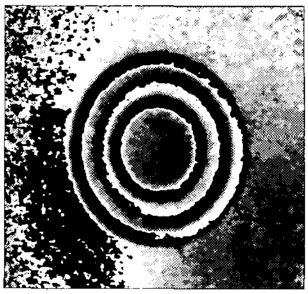
Fig. 6 phase map obtained by shifting 100μm

Fig. 6 is one of the phase map that are produced by shifting 100μm to perform the incremental addition image. If the phase map shifted as much as 100μm by micrometer is added, it is able to display the final distance.

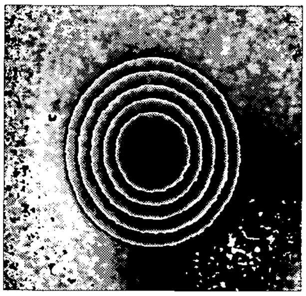
Fig. 7 displays incremental addition images of 8 phase maps obtained by shifting 100μm each. All of the 8-shifting distance is 800μm. Fig. 8 displays incremental addition images of 6 phase maps obtained by shifting 130μm each. Total shifting distance is 780μm. If this shifted distance is not used in the incremental addition image method, it is the shifted displacement quantity limited by the decorrelation effect of fringe. The more images are added, the more the shifted displacement quantity is increased and the number of fringe contour is increased but there is no the decorrelation effect. The curved pattern of fringe is a noise. The more images are added, the less the curved pattern and the noise are involved. Therefore, the improved fringe pattern with the decreased noises is shown in Fig. 7, 8.



(a) Incremental image by 2th addition

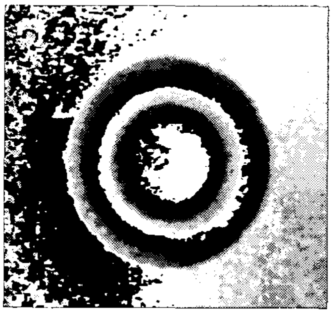


(b) Incremental image by 4th addition

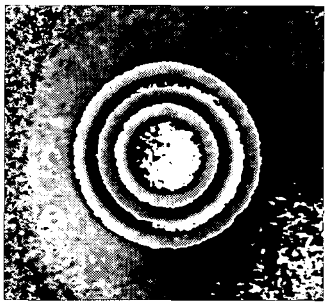


(c) Incremental image by 7th addition

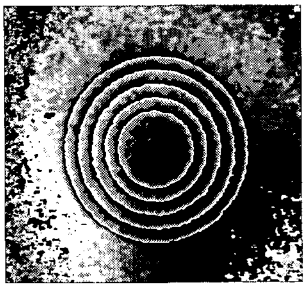
Fig. 7 Incremental addition images of phase maps obtained by shifting 100μm each.



(a) Incremental image by 1th addition



(b) Incremental image by 3th addition



(c) Incremental image by 5th addition

Fig. 8 Incremental addition images of phase maps obtained by shifting 130μm each.

7. Conclusions

The shape measurement of the 3-D object was accomplished by using the collimated beam. And, in order to overcome the limit of deformation and to improve the interference fringes quantitatively and qualitatively, the incremental addition image method was applied.

Based on the geometric analysis of the speckle interferometry system, the theoretical formula was derived to obtain the shape information of the 3-D object by using the incremental addition image. And the 3-D shape measurement for the specimen with steps on its surface was accomplished to estimate the performance of the speckle interferometer using collimated beam. Additionally, the incremental addition image method was applied to overcome the limit of a deformation restricted by the decorrelation effect through moving the collimated beam tinily. Therefore the interference fringe could be improved quantitatively and qualitatively.

In this study, the incremental addition image method was described and the study approved its possibility through the practical experiments. There will be the consequential study on the analysis for the improved accuracy and the error by removing the noises. It will be considered as the basic data on measurement of the deformation and the surface roughness.

Acknowledgement

This research was supported by Mechatronics Research Center (MRC) in Chonbuk National University, Chonju, Korea. MRC is designated as a Regional Research Center appointed by the Korea Science and Engineering Foundation (KOSEF), Chollabukdo Provincial Government and Chonbuk National University. I thank MRC.

References

1. R. Jones and C. Wykes, Holographic and Speckle Interferometry, 2nd ed., Cambridge Univ. Press, pp. 165-196, 1989.
2. X. Peng, H. Y. Diao, Y. L. Zou and H. Tiziani, "Contouring by Modified Dual-Beam ESPI Based on Tilting Illumination Beams," Optik(Stuttgart), Vol. 90, pp. 61-64, 1992.
3. R. Rdriguez-Vera, D. Kerr and F. Mendoza- Santoyo, "Electronic Speckle Contouring," Opt. Soc. Am., Vol. 9, pp. 2000-2008, 1992.
4. B. D. Bergquist and P. Montgomery, "Contouring by Electronic Speckle Pattern Interferometry," Proc. Soc. Photo-Opt. Instrum. Eng., Vol. 599, pp. 185-195, 1985.
5. X. Peng, H. Y. Diao, Y. L. Zou and H. Tiziani, "Geometry for Contouring by Electtronic Speckle Pattern Interferometry Based on Shifting Illumination Beams," Appl. Opt., Vol. 31, pp. 6616-6621, 1992.
6. Kang, Young June and Kim, Gye Sung, "A study on Shape Measurement by Using Electronic Speckle Pattern Interferometry," Journal of the Korean Society of Precision Engineering 15, No. 10, pp. 156-164, 1998.
7. K. Creath, "Phase-Shifting Speckle Interferometry," Appl. Opt., Vol. 24, pp. 3053-3058, 1985.
8. T. Floureux, "Improvement of Electronic Speckle Fringes by Addition of Incremental Images," Opt. Laser Technol., Vol. 25, No. 4, pp. 255-258, 1993.
9. M. Hertwig, T. Flourcux and T. Flemming, "Application of Recently Improved Electronic Speckle Pattern Interferometry by Addition of Incremental Images," Proc. Soc. Photo-Opt. Instrum. Eng., Vol. 2340, pp. 124-133, 1994.
10. M. Hertwig, "Application of Improved Speckle Contouring Technique to Surface Roughness Measurement," Optics and Lasers in Engineering, Vol. 26, pp. 115-130, 1997.